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Initial Assessment of the Ares I–X Launch Vehicle Upper Stage to Vibroacoustic Flight Environments

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Abstract

The Ares I launch vehicle will be NASA's first new launch vehicle since 1981. Currently in design, it will replace the Space Shuttle in taking astronauts to the International Space Station, and will eventually play a major role in humankind's return to the Moon and eventually to Mars. Prior to any manned flight of this vehicle, unmanned test readiness flights will be flown. The first of these readiness flights, named Ares I–X, is scheduled to be launched in April 2009. The NASA Glenn Research Center is responsible for the design, manufacture, test and analysis of the Ares I–X Upper Stage Simulator (USS) element.

As part of the design effort, the structural dynamic response of the Ares I–X launch vehicle to its vibroacoustic flight environments must be analyzed. The launch vehicle will be exposed to extremely high acoustic pressures during its lift-off and aerodynamic stages of flight. This in turn will cause high levels of random vibration on the vehicle's outer surface that will be transmitted to its interior. Critical flight equipment, such as its avionics and flight guidance components are susceptible to damage from this excitation.

This study addresses the modelling, analysis and predictions from examining the structural dynamic response of the Ares I–X upper stage to its vibroacoustic excitations. A statistical energy analysis (SEA) model was used to predict the high frequency response of the vehicle at locations of interest. Key to this study was the definition of the excitation fields corresponding to lift off acoustics and the unsteady aerodynamic pressure fluctuations during flight. The predicted results will be used by the Ares I–X Project to verify the flight qualification status of the Ares I–X upper stage components.

Introduction

Within the goals of NASA's Vision for Space Exploration, is the design and development of America's newest launch vehicle, the Ares I Crew Launch Vehicle (CLV). Ares I is a two stage launch vehicle which will lift more than 55,000 lb including a manned astronaut crew to low earth orbit. In conjunction with the more powerful (290,000 lb payload capability) Ares V cargo launch vehicle (CaLV), these vehicles will return humans to the Moon and eventually onto Mars.

The first stage (FS) of the Ares I vehicle will consist of a single five-segment PBAN (Polybutadiene Acrylonitrile) solid rocket booster (SRB) derived from the Space Shuttle's SRB system. The second or upper stage of the Ares I vehicle will utilize a liquid oxygen/liquid hydrogen J-2X engine evolved from the Apollo/Saturn-era J-2 upper stage engine. Inline and above this upper stage will be the Orion Crew Exploration vehicle (CEV) consisting of the spacecraft adapter (SA), service module (SM), crew module (CM), and launch abort system (LAS).

As with any newly designed launch vehicle, and particularly for a manned vehicle, it is important to flight test the vehicle's design capability and ability to control. To this end, there are a series of unmanned developmental flight readiness tests that will be performed. The first of these test flights will be the launch of the Ares I–X flight test vehicle (FTV) shown in figure 1. The Ares I–X flight is currently scheduled for April 2009. The primary purpose of the Ares I–X suborbital flight is to demonstrate the first stage flight control for a vehicle that is dynamically similar to the Ares I. Data collected from this flight will aid in validating Ares I design tools and methods regarding loads and dynamics, aerodynamics, guidance, navigation and control, roll torque, and first stage separation and recovery.

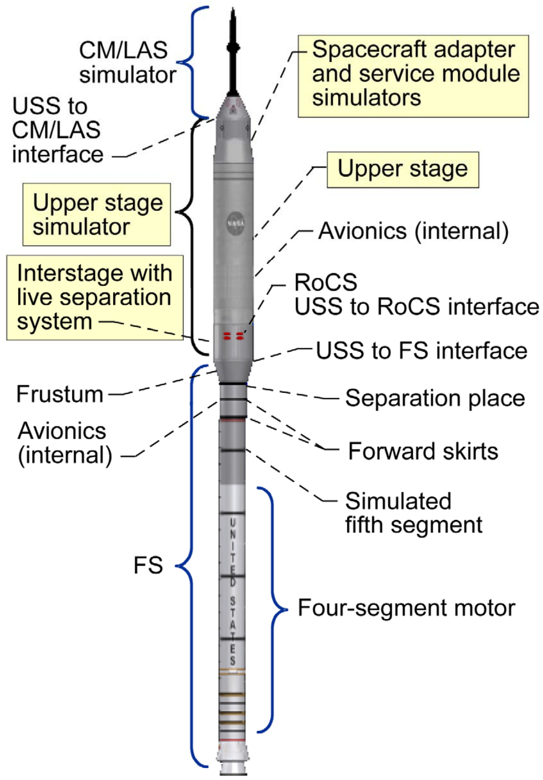

Figure 1.—Ares I–X Flight Test Vehicle (FTV).

The NASA Glenn Research Center is responsible for the design, manufacture, test and analysis of the Ares I–X Upper Stage Simulator (USS) element. The USS is essentially an inert mass simulator designed to provide the correct outer mold line (OML), mass, and center of gravity. The USS will simulate the liquid propellants with ballast mass assemblies and will not contain an operating engine or simulator. The USS is constructed of several large, cylindrical segments, commonly called “tuna cans”, which are stacked and bolted together (fig. 2) to represent the upper stage, SA and SM. Internal to each “tuna can” is a work platform and associated access ladders to facilitate the assembly.

Since several avionics packages, booster motors, and the USS separation system are to be located within the USS, it is important to define the vibroacoustic environments to insure the proper qualification of these components. To this end, Statistical Energy Analysis (SEA) was used to model and predict these environments (ref. 1).

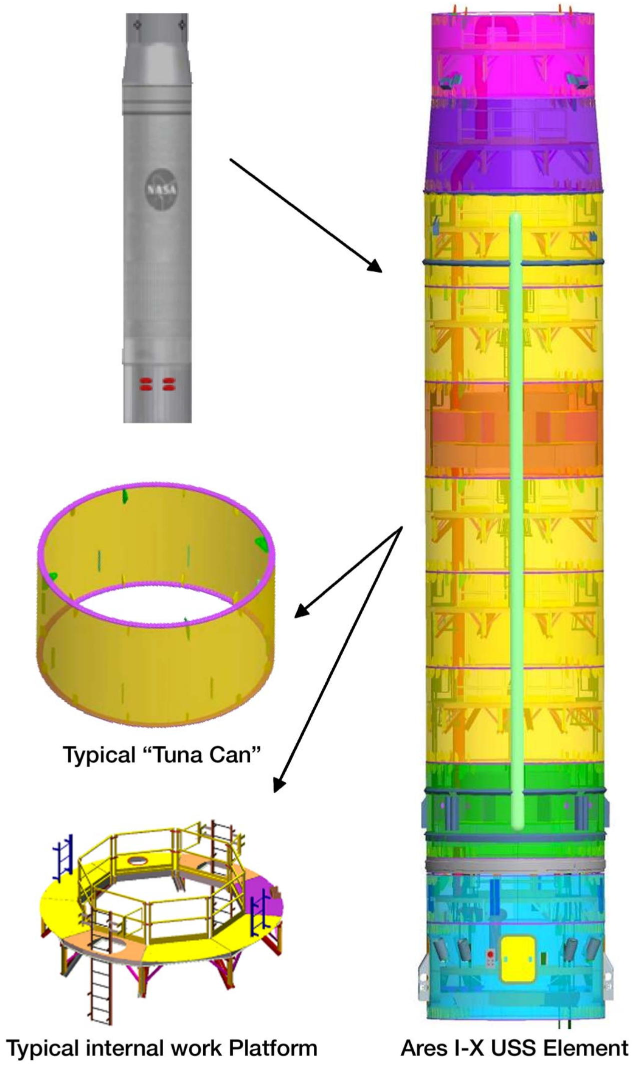

Figure 2.—USS element description.

SEA Model Development

The Ares I–X USS SEA model was developed based on available solid models of the October 2006 structural design configuration (ref. 2). The commercial vibroacoustic software VA One 2006 (ref. 3) was used for this study. Because it is relatively easy to import Finite Element (FE) and Computer Aided Design (CAD) model geometry directly into VA One to build the SEA subsystems, the more complicated internal structural subsystems were created from imported FE geometry while the simpler external cylindrical shells were created manually. An axisymmetric, half-model of the USS was created to facilitate both the construction of internal secondary structures and the visualizing/selecting data recovery items, while reducing computation time.

The USS elements modelled included the cylindrical skin, internal work platforms, ballast assemblies and internal air volumes. For the tuna can skins, platforms and ballasts, flat panel and singly curved shell SEA subsystems were used (fig. 3). SEA acoustic cavities represented the internal air cavities (fig. 4). Each of the skin subsystems was connected to a SEA semi-infinite fluid (SIF) in order to describe the fluid loading on the structure and to provide a dissipative sink. Since minimizing weight was not critical for the Ares I–X, the “battleship” design of the USS indicated that very simple uniform, isotropic steel material and physical properties could be assigned to all the primary and secondary structural subsystems.

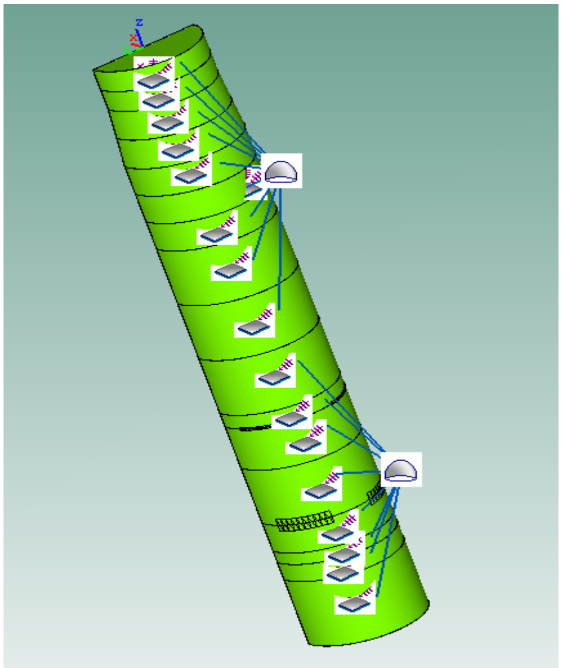

Figure 3.—External view of USS SEA model.

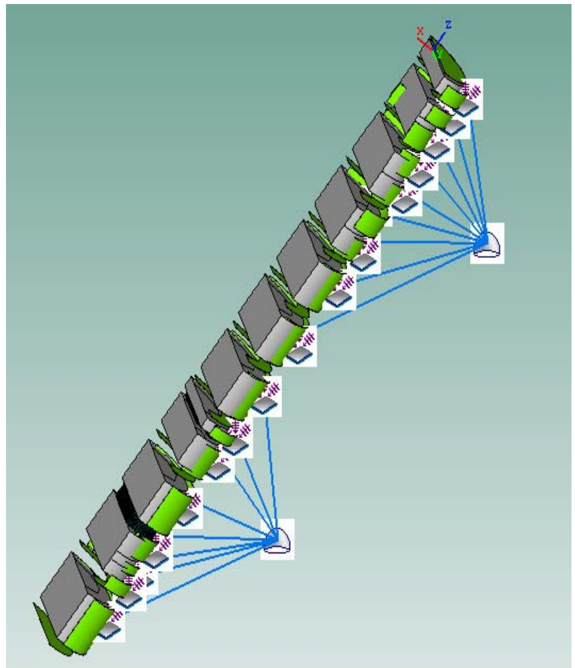

Figure 4.—Internal view of USS SEA model.

To check the frequency range of applicability of the SEA model, the modes in band for the plate and shell structures were quickly checked. The subsystem modal density indicated that in order to maintain a minimum of 3 modes-in-band, the analysis would be valid no lower than 80 Hz.

SEA Excitation Implementation

Three mission events were identified for the prediction of worst-case environments: lift-off, transonic flight, and flight at maximum dynamic pressure (max Q). Each of these flight regimes required that an external environment be defined and then applied to the skin subsystems so that structural responses could then be predicted.

The external environments are modelled as either a diffuse acoustic filed (DAF) or a turbulent boundary layer (TBL) excitation in VA One. In general, these excitations differ in the assumed spatial correlation of the sound field, and require user-specified sound pressure level (SPL) autospectrum and cross-spectrum.

For the turbulent boundary layer excitation, figure 5 (ref. 4) shows the equation for the spatial correlation function, and plots the cross-correlation coefficients both along the flow and across the flow for the transonic and max Q flight regimes at 400 Hz. Conservative results are obtained by simply using the VA One default values for the TBL parameters $c_\zeta(\omega)$, $c_\eta(\omega)$, $\alpha(\omega)$, $\beta(\omega)$ and σ.

For the DAF excitation, the pressure fluctuations are phase-correlated at points that are close together relative to an acoustic half-wavelength; the spatial cross-correlation function is described by a sinc function, $\sin(kr)/(kr)$. Figure 6 plots an example of the DAF and TBL cross-correlation functions for comparison (ref. 4).

A DAF excitation was used to model the lift-off event where the only source of fluctuating pressure loads is the solid rocket motor noise. It has been tradition to simulate the lift-off acoustics using diffuse acoustic fields both in analysis and ground testing. This approach has been found to be conservative despite the fact that the lift-off acoustics might be better represented by a progressive wave field. The lift-off acoustic SPL environments (ref. 5) were calculated using the Vehicle Acoustic Environment Prediction Program (VAEPP) which was specifically developed to predict acoustic pressures and power levels of rocket systems given various geometric and performance parameters (ref. 6).

$$R(\xi,\eta,\omega)=\underbrace{\left(e^{-c_{\xi}(\omega)\sqrt{k_{\xi}^{2}(\omega)+k_{\eta}^{2}(\omega)+\left(\frac{1}{3\delta_{i}^{*}}\right)^{2}}\,|\xi|}\cos\left(k_{\xi}(\omega)\xi\right)\right)}_{\text{Along Flow}}\underbrace{\left(e^{-c_{\eta}(\omega)\sqrt{k_{\xi}^{2}(\omega)+k_{\eta}^{2}(\omega)+\left(\frac{1}{3\delta_{i}^{*}}\right)^{2}}\,|\eta|}\cos\left(k_{\eta}(\omega)\eta\right)\right)}_{\text{Across Flow}}$$

$$k_{\xi}=\alpha(\omega)\frac{\omega}{U_C'} \qquad k_{\eta}=\beta(\omega)\frac{\omega}{U_C'} \qquad U_C'=\sigma U \qquad \delta^{*}=\frac{\delta}{8}=\frac{0.37}{8}\frac{X_0}{\mathrm{Re}^{1/5}}$$

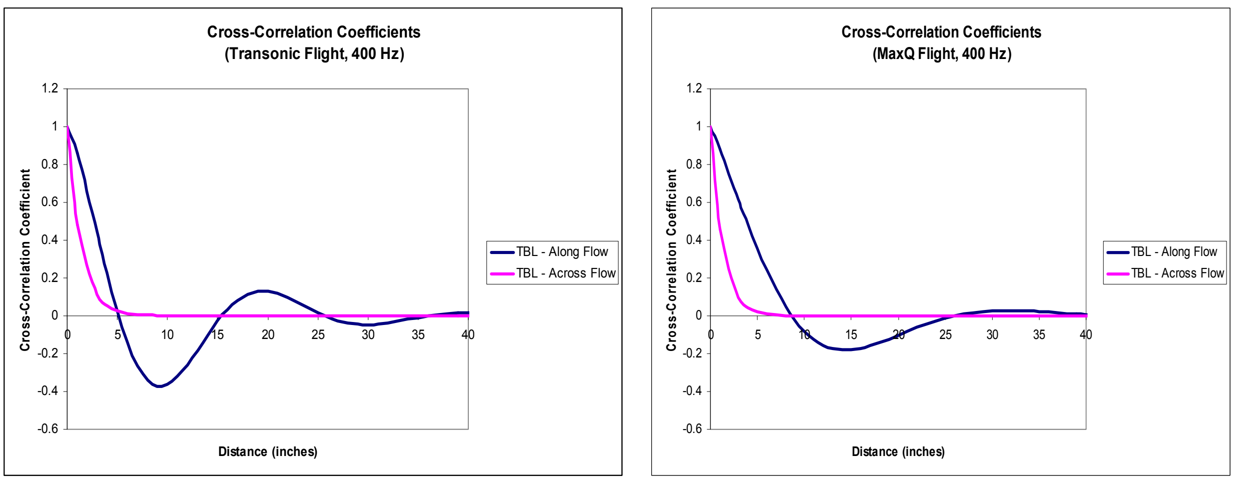

Figure 5.—Turbulent boundary layer excitation definition (ref. 4)

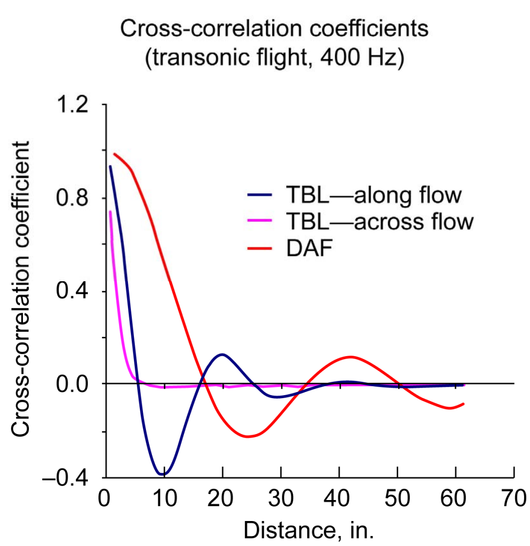

Figure 6.—Comparison of DAF and TBL cross-correlation coefficients (ref. 4).

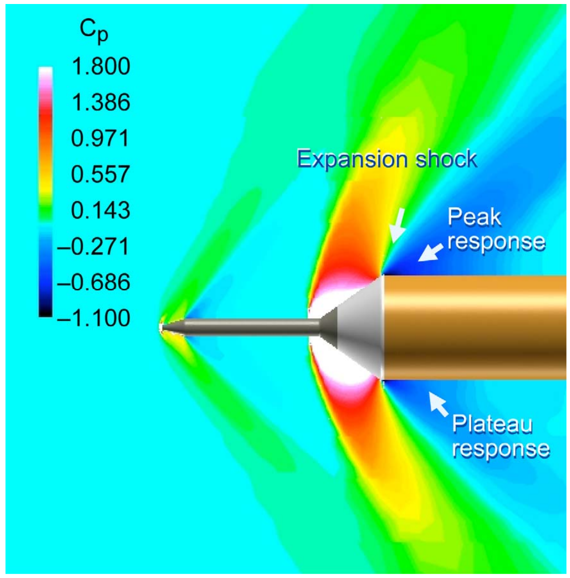

Figure 7.—CFD visualization of C_p (ref. 7).

During the transonic and max Q phases of flight, the vehicle has significant velocity and experiences fluctuating pressures due to the formation of turbulent boundary layers across the structure. Before implementing the TBL excitations, certain flight characteristics and fluid properties at the altitudes corresponding to transonic and max Q flight are needed. A nominal trajectory analysis provided the free stream flow velocity (U_0), fluid density at altitude (ρ), fluid kinematic viscosity at altitude (ν) and fluid speed of sound at altitude (c_0). Also required is the distance (X_0) from the leading edge of the turbulent boundary layer to the center of the pressure load on the surface of each subsystem. Based on early computational fluid dynamics (CFD) visualizations of the static pressure coefficient (C_p), an expansion shock (fig. 7) was observed occurring at the forward-most edge of the USS (ref. 7). Therefore, the assumption was made that this constituted the leading edge for the measurement of X_0 for all subsystems excited by the TBL.

The autospectrum component of the TBL definition was based on the lift-off SPL with additional correction factors included for peak and plateau responses affecting the SA and SM subsystems (fig. 7). Although this is a crude approximation, no CFD or wind tunnel aeronoise data was available at this early stage of hardware development. As a result of this approximation, the transonic and max Q predictions may not be conservative.

Discussion of Predicted Structural Responses

Application of these environments to the SEA model resulted in spatial average predictions of the structural response for each SEA subsystem such as a tuna can. In an attempt to capture the spatial variability within each SEA subsystem, a further post-processing step was taken following the method described in references 8 and 9 to calculate the maximum predicted environment (MPE) for each subsystem using the SEA mean prediction and the expected variance based on the modal density. This method provides a level which statistically corresponds to the P95/C50 (95th percentile with 50 percent confidence). These levels will be used to assess the random vibration qualification status of avionics packages and other flight components, along with providing guidance on selection of component mounting locations for Ares I–X.

Figure 8 shows the predicted MPE levels for the various SEA structural subsystems for the lift-off environment. The predicted results may be grouped into four families: the two ballast assemblies, the steel tuna cans and the separation ring. The lowest predicted response corresponds to massive ballast subsystems simulating the liquid oxygen (LOX) propellant. The next highest response is that of the

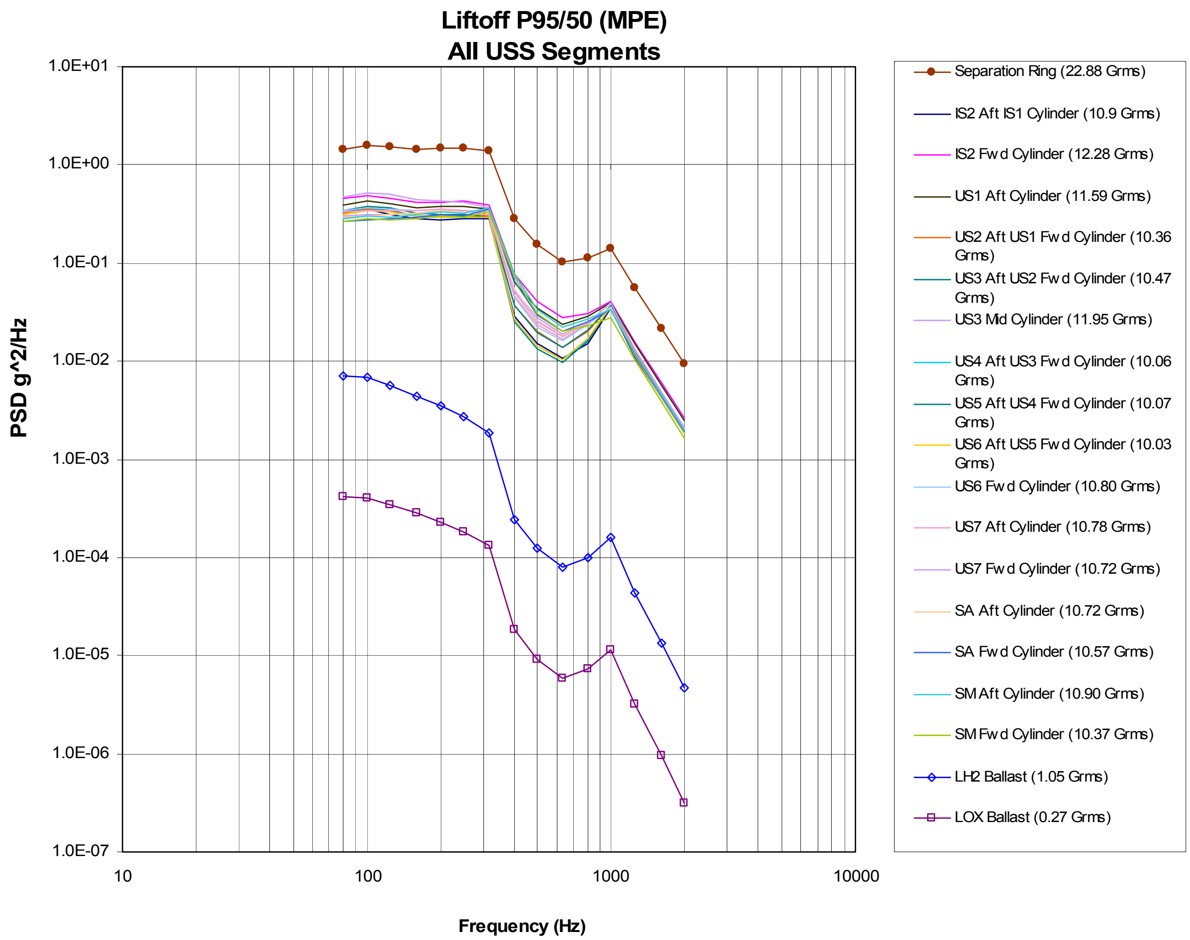

Figure 8.—P95/C50 predicted level for USS during lift-off.

ballast simulating the liquid hydrogen (LH_2) propellant. These two levels are unique to the Ares I–X flight and provide a great opportunity for mounting flight components that may be sensitive to higher vibration levels. The third family of responses consists of all the steel tuna cans and shows very little variability between cans. Finally, the fourth family, corresponding to the highest response, is for the separation ring subsystem. Because the separation ring is composed of a different, less dense material than all the other tuna cans, its response is greater.

The two prominent peaks in all the responses correspond to the ring (292 Hz) and coincidence (1019 Hz) frequencies for the cylindrical tuna cans. The ballast assemblies, although modelled as flat plates, exhibit the same characteristics. This is believed to be caused by the effective frequency filtering of the tuna cans on the input excitation.

Figure 9 shows the predicted MPE levels for a typical tuna can for the three flight regime excitations. In all cases, lift-off resulted in the highest response for the uniform USS cylindrical structures. Note that for hardware located on the CEV, where there are significant protuberances and OML geometry changes, this would not be true. Also recall that the transonic and max Q autospectra were not well defined at the time of this analysis. Therefore, the associated structural response predictions may not be conservative. There were no significant differences in the response from the transonic and max Q regimes.

In figure 9, it is noticed that some of the prominent peaks of the lift-off response are shifted or not present in the transonic and max Q responses. Part of the reason for this lies in the fact that due to SEA reciprocity, the power input to the structure for the lift-off DAF excitation is governed by the same parameters as the radiation efficiency, σ_{rad}. To help gain insights into the responses, figure 10 shows the DAF radiation efficiency for the same subsystem as identified in figure 9. The peaks in the response and

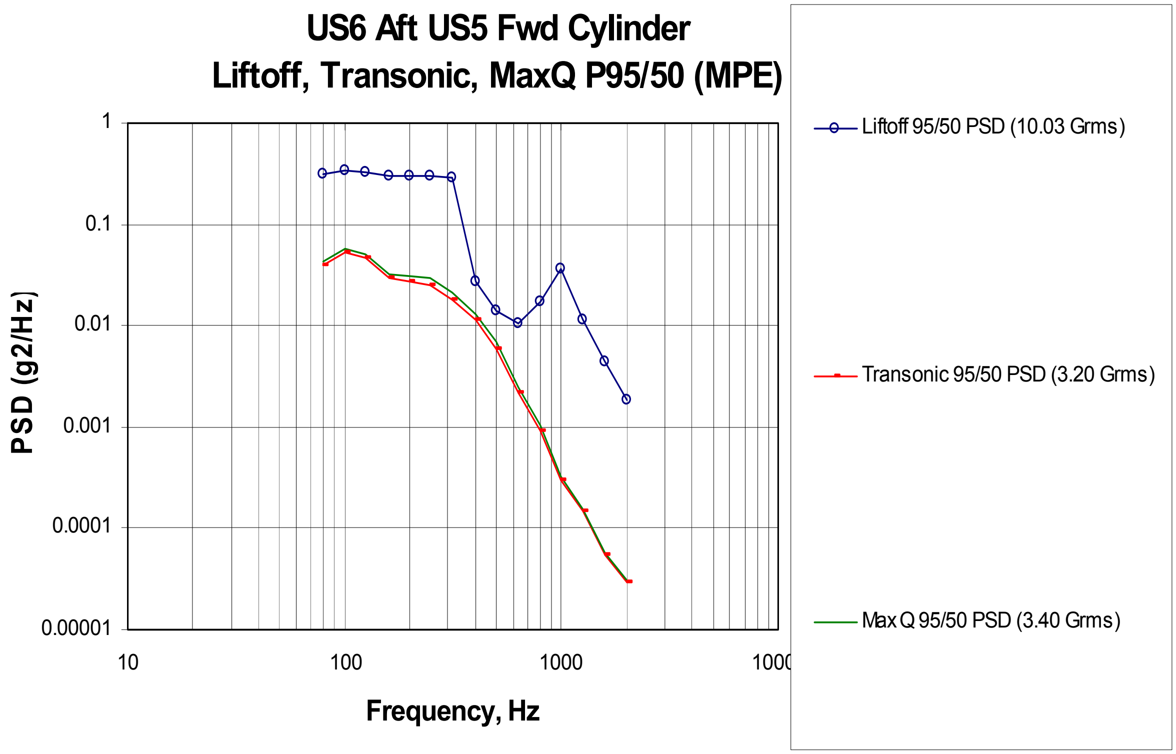

Figure 9.—Typical tuna can structural response for lift-off, transonic and max Q excitations.

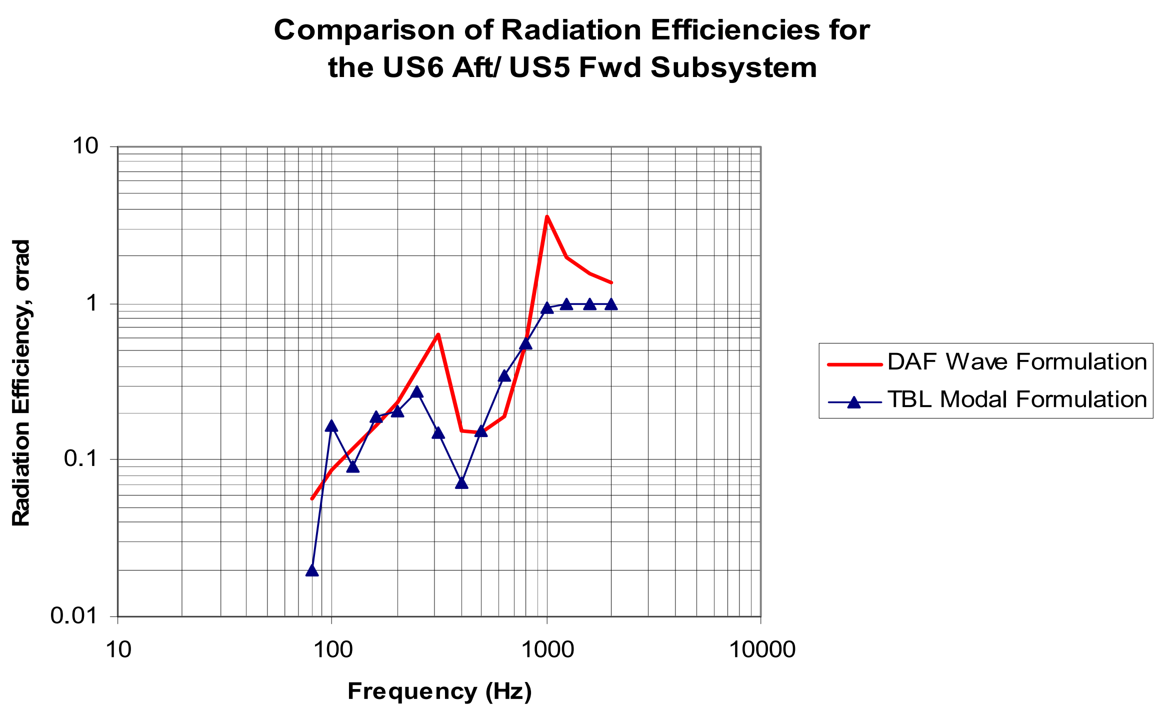

Figure 10.—Radiation efficiencies for the US6 Aft/US5 Fwd subsystem.

radiation efficiency correspond well. However, for the transonic and max Q TBL excitation, the power input is calculated in VA One using a modal formulation (instead of the wave formulation of the DAF). The differences in σ_{rad} due to the different formulations are also shown in figure 10. It can be seen that the modal formulation produces less "sharp" peaks as the wave calculation and also tends to "smear" and shift some of the peaks. This contributes to the lower structural response seen in the TBL excitation relative to the response of the lift-off excitation for the same SPL.

Future work includes continuing Ares I–X USS vibroacoustic assessments with updated and refined structural design information. In addition, as wind tunnel test data becomes available and more detailed aeronoise excitation models are developed for the transonic and max Q regimes, revised structural response predictions will be made.

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